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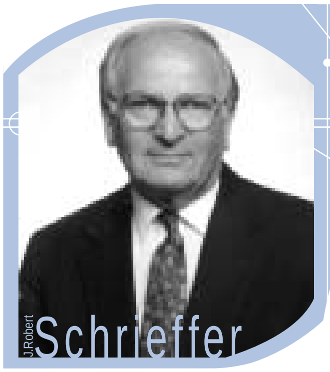

from the Chief Scientist's Desk

The role of strong Coulomb interactions and randomness has been a long standing problem in condensed matter physics. The Coulomb potential tends to localize electrons into a so called Wigner lattice while randomness tends to pin electrons in regions of low potential. Dr. Popović has made forefront discoveries showing that electrons in two dimensions show glassy behavior between Wigner and random behavior. The noise spectrum of this system is particularly interesting.

Glass Transition in a Two-Dimensional Electron System in Silicon

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The possibility of a metal-insulator transition (MIT) in two dimensions (2D) has been a subject of intensive research in recent years[1] but the physics behind this phenomenon is still not understood. Since the apparent MIT occurs in the regime where both electron-electron interactions and disorder are strong, it has been suggested that the 2D system undergoes glassy ordering in the vicinity of the MIT. The proposals include freezing into a Coulomb,[2,3] Wigner,[4] or spin glass.[5] It is clear that understanding the nature of the insulator represents one of the crucial issues in this field. Here, we report the first observation and study of glassy behavior in a 2D system in semiconductor heterostructures. The glass transition is manifested by a very abrupt onset of a specific type of random-looking slow dynamics, together with other signs of cooperativity. Our results strongly suggest that the

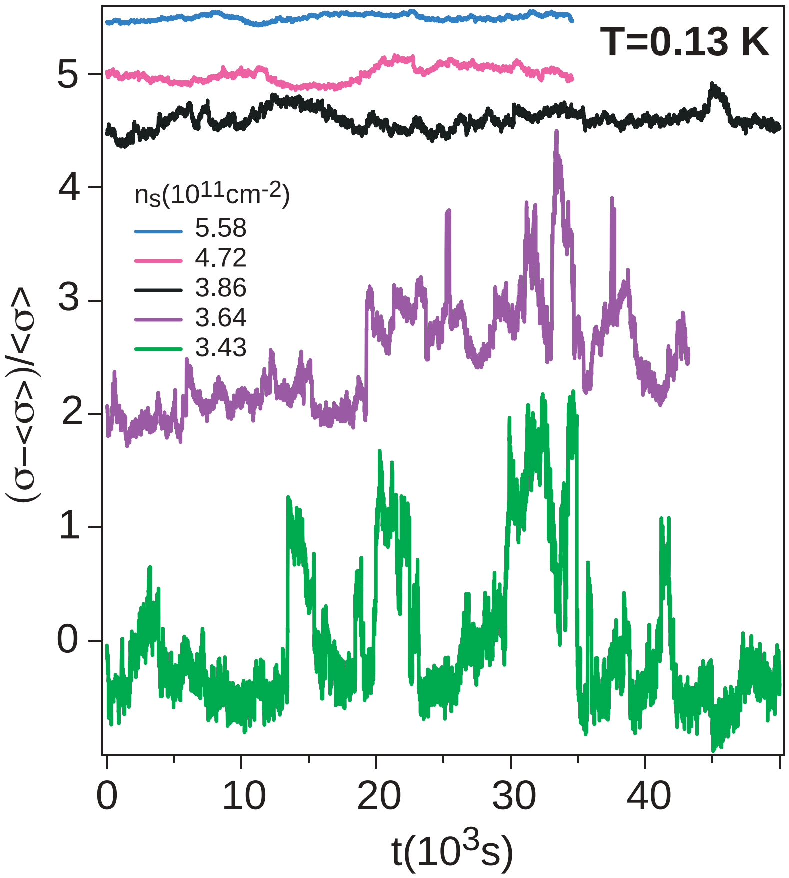

Figure 1. Relative fluctuations of σ *vs.* time for several n_s at T=0.13 K. Different traces have been shifted for clarity, starting with the lowest n_s at bottom and the highest at top.

glass transition occurs in the metallic phase as a precursor to the MIT, in agreement with recent theory.[6] Studies of both low- and high-mobility samples demonstrate that the glassy freezing of a 2D electron system in the vicinity of the MIT is a universal phenomenon in Si inversion layers.

Measurements of the conductivity σ of a 2D electron system in Si metal-oxide-semiconductor field-effect transistors (MOSFETs) were carried out as a function of time over a wide range of electron densities n_s and temperatures T. Such resistance noise studies have proven to be a powerful and, perhaps, the most important tool in unraveling the nature of glassy ordering and dynamics in metallic spin glasses.[7] Fig. 1 shows the relative fluctuations of σ (where $\langle\ldots\rangle$ denotes averaging over time) for a few selected n_s at T=0.13 K. The data were obtained[8] on a highly disordered sample, with a peak mobility of only 0.06 m^2/Vs at 4.2 K. It is quite striking that, for the lowest n_s, the fluctuations are of the order of 100%. In addition to rapid, high-frequency fluctuations, both abrupt jumps and slow changes over periods of several hours are also evident. The noise decreases with increasing either n_s or T, as described in more detail below. The analysis of the time-averaged conductivity $\langle\sigma\rangle$ as a function of T for different n_s (Fig. 2) shows that its overall behavior is similar to that of high-mobility Si MOSFETs. For example, a metallic-like behavior with $d\langle\sigma\rangle/dT<0$ is observed at the highest n_s, and $d\langle\sigma\rangle/dT$ changes sign when $\langle\sigma(n_s^*)\rangle\approx 0.5$ e^2/h. A detailed analysis of $\langle\sigma(n_s,T)\rangle$ in the insulating and quantum critical regimes shows[8] that the MIT occurs at $n_c=(5.0\pm0.3)\mathrm{x}10^{11}\mathrm{cm}^{-2}$. However, while $\delta\sigma/\langle\sigma\rangle$ $(\delta\sigma=\langle(\sigma-\langle\sigma\rangle)^2\rangle^{1/2})$ does not

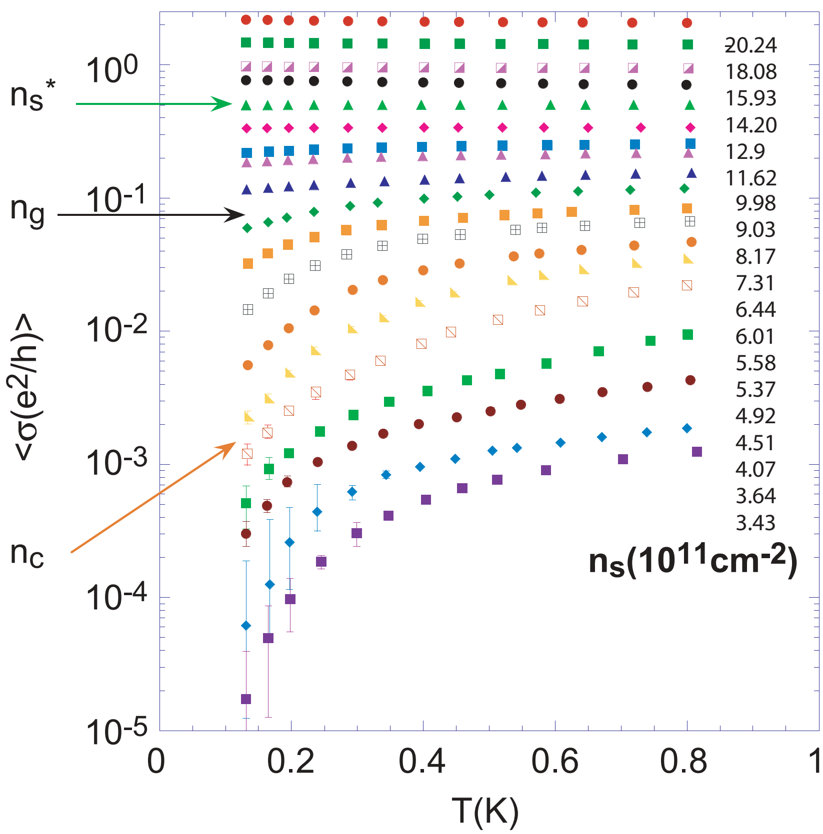

Figure 2. $\langle\sigma\rangle$ *vs.* T for different n_s. The data for many other n_s have been omitted for clarity. The error bars show the size of the fluctuations. n_s^*, n_g and n_c are marked by arrows. They were determined as explained in the main text.

depend on n_s at high densities an exponentially large increase of noise is observed when n_s is decreased below $n_g=(7.5\pm0.3)\times10^{11}cm^{-2}$ [Fig. 3(a)]. This effect becomes more pronounced as T is lowered.

In order to understand the origin of this surprising increase in noise, we have carried out a detailed spectral analysis[8] of the fluctuations $(\sigma-\langle\sigma\rangle)/\langle\sigma\rangle$. The normalized power spectra $S_I(f)=S(I,f)/I^2$ (f-frequency, I-current) were obtained in the $f=(10^{-4}-10^{-1})$ Hz bandwidth, where they follow the well-known empirical law $S_I\propto1/f^{\alpha}$. We find that, while $S_I(f)$ does not depend on n_s at high densities, it increases enormously, by up to six orders of magnitude at low f, as n_s is reduced below n_g. It is clear that the observed giant increase of $\delta\sigma/\langle\sigma\rangle$ for $n_s<n_g$ [Fig. 3(a)] reflects a *sudden and dramatic slowing down of the electron dynamics.* This is attributed to the freezing of the electron glass. Perhaps even more remarkable is a sharp jump of the exponent α at $n_s\approx n_g$ [Fig. 3(b)]. While $\alpha\approx1$ for $n_s>n_g$, $\alpha\approx1.8$ below n_g, reflecting a sudden shift of the spectral weight towards lower frequencies. In general, such noise with spectra closer to $1/f^{2}$ than to $1/f$ is typical of a system far from equilibrium, in which a step does not lead to a probable return step. Indeed, we also have the analysis of higher order statistics[9] (non-Gaussianity or second spectra[7]) of the noise, showing an abrupt change to the sort of statistics characteristic of complicated multistate systems just at the density n_g at which α jumps. In particular, the results demonstrate that, while $1/f$ noise

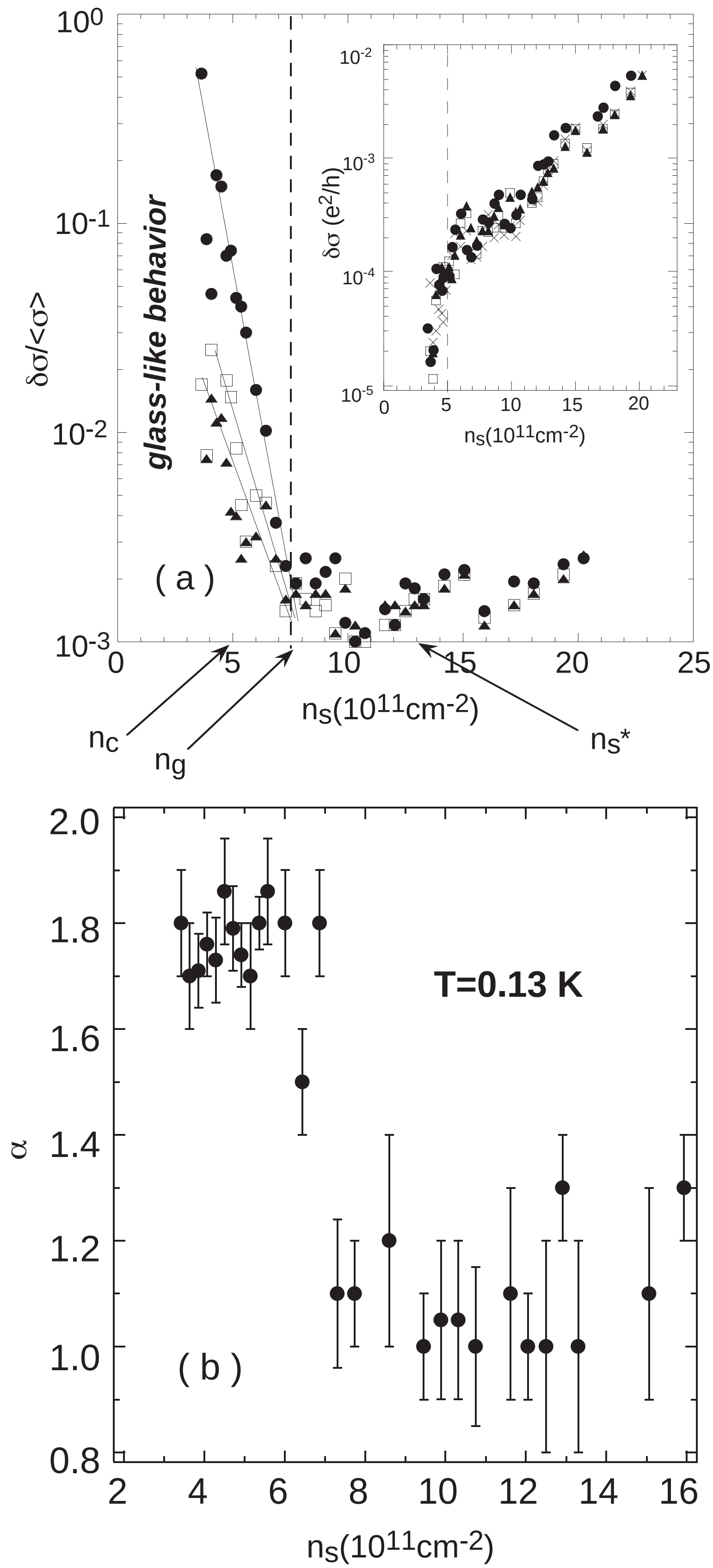

Figure 3. (a) $\delta\sigma/\langle\sigma\rangle$ (main) and $\delta\sigma$ (inset) *vs.* n_s at different T (•: 0.130 K, x: 0.196 K, □: 0.455 K, ▲: 0.805 K). Main: n_s^*, n_g, and n_c are marked by arrows. The vertical dashed line shows the region of densities $n_s<n_g$ where various glassy properties have been observed. Inset: The vertical dashed line shows the location of the critical density n_c for the MIT, where a sudden and dramatic change in the $\delta\sigma(n_s)$ occurs. (b) The exponent α, which characterizes the frequency dependence of the noise power spectrum $S_I\propto1/f^{\alpha}$, *vs.* frequency for several n_s. The jump in α occurs when $n_s=n_g$.

at $n_s > n_g$ is produced by uncorrelated fluctuators, in the glassy phase ($n_s < n_g$) the system wanders collectively between many metastable states related by a kinetic hierarchy. Metastable states correspond to the local minima or "valleys" in the free energy landscape, separated by barriers with a wide, hierarchical distribution of heights and, thus, relaxation times. Intervalley transitions, which are reconfigurations of a large number of electrons, thus lead to the observed strong, correlated, $1/f$-type noise, remarkably similar to what was observed in spin glasses with a long-range correlation of spin configuration.[7] We also note that other manifestations of glassiness, such as long relaxation times and history dependent behavior, have been observed for $n_s < n_g$. Glassy freezing occurs in the regime of very low $\langle\sigma\rangle$, apparently as a precursor to the MIT. The existence of such an intermediate ($n_c < n_s < n_g$) metallic glass phase is consistent with theoretical predictions.[6]

Measurements of transport and noise have been carried out[9] also on a 2D electron system in Si in the opposite limit of very low disorder, in samples with a peak mobility of 2.5 m^2/Vs at 4.2 K. We find that, similar to the case of low-mobility samples, the behavior of several spectral characteristics of noise indicates a sudden and dramatic slowing down of the electron dynamics at a well-defined electron density n_g, corresponding to the transition to a glassy phase with long-range correlations between fluctuators, in agreement with the hierarchical picture of glassy dynamics. Since the two sets of devices differ considerably by their peak mobility, which is a rough measure of the disorder, as well as by their geometry, size, and many fabrication details, we conclude that the observed glass transition is a universal phenomenon in Si inversion layers. The experiments, however, have also revealed an important difference between low- and high-mobility samples. In low-mobility devices, $n_g \approx 1.5 n_c > n_c$, whereas in high-mobility structures the onset of glassy dynamics seems almost to coincide with the MIT, *i.e.* $n_g \approx n_c$ ($\approx n_s^*$). In other words, the size of the intermediate glass phase, which separates the ordinary 2D metal and the (glassy) insulator, depends strongly on disorder, becoming extremely small in high-mobility samples. This is consistent with recent predictions of the model of interacting electrons near a disorder-driven MIT.[6]

In summary, studies of low-frequency resistance noise have demonstrated that the 2D electron system in silicon undergoes glassy freezing in the vicinity of the metal-insulator transition. The properties of the glass phase are consistent with the hierarchical picture of glassy dynamics, similar to spin glasses with long-range correlations. These results have great relevance for the development of a theory for the 2D MIT, and for disordered, strongly correlated systems in general. Future noise experiments in parallel magnetic fields should provide important information about the role of the spin degrees of freedom in these phenomena.

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